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Trip Report:
Electric Power Research Institute (EPRI) Workshop
Colorado Springs, 12-13 June 1991

MAGNETIC FIELD CONSIDERATIONS
FOR LOW-VOLTAGE GROUNDING

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Attendance at the Electric Power Research Institute (EPRI) Workshop on "Magnetic Field Considerations for Low-Voltage Grounding" provided useful contacts and considerable information that will assist our research into techniques for mitigating electromagnetic fields. This report summarizes the presentations and discussions at the Workshop, and makes recommendations on the basis of Workshop experience.

1. Introduction

Despite the lack of conclusive evidence pointing to any detrimental health effects due to electromagnetic fields (EMF), recent legislation in the United States and elsewhere has leaned towards establishing arbitrary limits on magnetic field levels from electrical systems. There is thus a great deal of interest from electrical utilities in examining various strategies for managing magnetic fields in general.

One of the main components of human EMF exposure is magnetic fields associated with neutral return currents, or ground currents, on residential water service lines. These fields can constitute up to 40% of total magnetic field exposure. The mitigation of ground current magnetic fields was examined recently at "Magnetic Field Considerations for Low-Voltage Grounding", a Workshop held at Colorado Springs, U.S.A., on 12-13 June 1991, and sponsored by the U.S. Electric Power Research Institute (EPRI).

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Approximately 75 participants attended the Workshop; roughly 60% of that number represented electrical power utilities, 13% represented electrical contractors, 13% represented other industries such as water and gas utilities, 7% represented universities and other research institutions and 7% represented private citizens' groups and public service institutions. The National Grid Company provided one delegate from the United Kingdom, while Ontario Hydro provided the lone Canadian participant.

The objectives of the Workshop were to:

- Provide a forum for discussion of why existing grounding practices have been adopted and what constraints must be observed in the consideration of revisions to current practice;
- Explore concepts for alternate designs that would reduce ground currents and their associated magnetic fields;
- Identify an appropriate research agenda.

Among the major topics of discussion at the Workshop were the following:

- (a) Update on Health Studies
- (b) Residential Measurements of Ground Current Magnetic Fields
- (c) Non-Residential Measurements of Ground Current Magnetic Fields
- (d) The U.S. National Electrical Code and Magnetic Fields
- (e) Residential Ground Currents: Diagnostics and Possible Fixes
- (f) Perspectives of Other Utilities
- (g) Recent Epidemiological Studies
- (h) Possible Alternate Grounding Designs

This report summarizes the major points of discussion at the Workshop, as well as some personal observations arising from discussions with other participants.

2. Update on Health Studies

Dr. Stanley S. Sussman, of the Environment Division of EPRI, gave an overview of current work on the health effects of magnetic fields. These include:

- A U.S. Department of Energy (DOE) epidemiological study involving 1000 cases and controls;

- A study by the U.S. Food and Drug Administration (FDA) on magnetic field health effects of devices such as X-ray machines, magnetic resonance imaging machines, and some appliances such as electric blankets;
- An extensive epidemiological and toxicological research program currently being proposed under the U.S. Environmental Protection Agency (EPA); and
- Other studies around the world, including those being done in Canada, the United Kingdom and Sweden.

The research effort in North America and around the world is growing and diversifying. Final results of these programs are anticipated by the mid-1990s.

One study focussed on at the Workshop is a recent epidemiological study by a group at the University of Southern California (USC), headed by Dr. John Peters. While the study is still to be published (in the *American Journal of Epidemiology*), some results are to be released at a forthcoming meeting of the Bioelectromagnetism Society (BEMS). General results were presented at the EPRI Workshop.

The USC study was a case-control study, based on 232 cases (children with leukemia) and controls, matched by sex, age and ethnicity. A telephone questionnaire with the children's parents ascertained residential history, parental occupations, the use of household appliances, as well as other factors. Exposures were characterized using the Wertheimer-Leeper wiring configuration code (WL code), as well as various spot measurements and time-weighted (24-hour) average measurements of the magnetic field. The results were as follows:

- While a slightly increased odds ratio (OR = 1.5) was found for children at residences with the highest time-weighted magnetic field measurements, this was found to be not statistically significant. No consistent exposure-response pattern was found.
- While a slightly increased odds ratio (OR = 1.3) was found for children at residences with high magnetic field spot measurements, this was found to be not statistically significant. No consistent exposure-response pattern was found.
- A moderately increased, statistically significant, odds ratio (OR = 2.5) was found for children at residences coded "high-current configuration" via the WL code.

Other conclusions of the USC study centred on appliances and possible confounders. Of 13 appliances evaluated, eight showed some association with increased cancer risk. However, of these, only two had statistically significant associations - hair dryers and black-and-white television sets. The rest exhibited nonsignificant results. In evaluating other, possibly confounding, exposure agents, the USC study found a statistically significant increased odds ratio for pesticide exposure (OR = 2.5).

In summary, the USC study found no significant association of leukemia with magnetic field exposure as characterized by spot measurements or time-weighted measurements. However, the USC study replicated the WL code association with leukemia, and found some possible association with appliance use.

3. Residential Measurements of Ground Current Magnetic Fields

3a. Residential Pilot Study

Dr. Luciano Zafanella, of General Electric (GE) and Manager of the EPRI High Voltage Transmission Research Center (HVTRC) in Lenox, Massachusetts, described preliminary measurements of ground currents and associated magnetic fields in 162 homes; this was in support of the 1000-subject study of the DOE, mentioned in section 1 above. Results were presented as ground current ratios $R = I_G/I_L$, where I_G represents the ground current and I_L represents the load current. The results showed that most homes (70%) exhibited $R = 0$, that is, no ground currents. For approximately 8% of the homes, $R = 0.5$, meaning that the ground current was roughly equal to the neutral return current, a significant fraction. In fact, for one home, the entire load current was flowing back through the ground current, and $R = 1$. This indicated a faulty neutral connection, which was subsequently fixed by the utility involved.

Actual measurements of the ground current were also reported. Again, the majority of homes exhibited near-zero ground currents, while the rest exhibited ground currents in the range of 1 to 5 A. Since the magnetic field is roughly proportional to the ground current, the same distribution is expected for the field profile. Survey measurements on a few of the houses pointed out that conductor location was important. When current flow occurs only on one side of the home, the average field throughout the home is low (0.07 μ T, or 0.7 mG, in the example discussed). When the ground current conductors are distributed throughout the home, the average field is higher (0.16 μ T in the example discussed).

Preliminary results were also presented on time-resolved fluctuations in the ground currents of some houses. It was pointed out that certain net current drops ("transients") could be identified as associated with the insertion of loads, possibly in other homes. This suggests that "tracer loads" could be used in order to follow the current flow through the neighborhood electrical conductor system.

3b. Work at the Magnetic Field Research Facility

Dr. Zafanella also reported results on the calculation and measurement of ground currents in a test residential neighborhood. This work was done in conjunction with Dave Mader and Russell Scheer of Ontario Hydro, at the HVTRC complex's Magnetic Field Research Facility (MFRF) in Lenox, Massachusetts. The facility includes an overhead distribution line and a water distribution system that can be connected in different ways to the neutral wires. The distribution line serves a two-story test residence as well as up to 18 other test residences simulated by load cabinets, through up to nine distribution transformers. For the measurements presented at the Workshop, a five-house neighborhood was simulated, including the two-story test residence and a single distribution transformer.

Preliminary measurements included the geometry of the conductors, the impedance of the water main, and ground currents at each test residence under the application of controlled loads. Theoretical work included formulation of the electrical network problem and its solution for the ground currents. The analytical method was shown to be able to predict ground currents from load currents within an accuracy of 20%, with joint resistances in the water main the most significant source of uncertainty.

Some other results of different simulations:

- Ground currents in a given house may be affected significantly by loads at other houses. In one of the examples discussed, a 1 A load at Residence 5 produced a ground current of about 0.1 A at Residence 3.
- The addition of a single residence and its associated load can raise the ground currents of all houses in the neighborhood.
- A bad neutral connection at a single residence can raise the ground currents in all houses in the neighborhood.
- Using an open bus instead of spun triplex wires for distribution resulted in an increase in ground currents by roughly 10 to 20%.
- Using nonconductive (plastic) pipes in the water distribution system results in a significant reduction of ground currents, with the actual reduction proportional to the ground rod impedance used.

4. Non-Residential Measurements of Ground Current Magnetic Fields

Dr. Gary B. Johnson, of GE and EPRI's HVTRC facility, reported on a pilot study of non-residential magnetic field sources. The measurement technique consisted of a general area survey using field mapping with a 3-axis gaussmeter, hand-held spot measurements and 24-hour field recordings. The pilot study focussed on utility plants, because they provided for a wide range of non-residential settings. This included office buildings, cafeterias, machine shops, stock rooms, substations and generating stations.

Ground currents were found on a variety of conducting paths: water mains, cable television sheaths, telephone lines, conduits, and even building structural steel. In one case, current flow was through a bolt attaching a distribution panel to the structural steel. In another case, current was found to be flowing from a conduit to steel floor joists; this led to the affected room having essentially a sheet of current underfoot, with a resultant average magnetic field of 0.5 to 1.2 μ T.

High grounding currents were also found to be associated with premature corrosion of pipes; currents of from 1 to 10 A were found on water pipes having a high degree of corrosion. This observation was interesting in light of later comments by representatives from the water utilities.

Very high magnetic fields were found to be associated with equipment and appliances, as expected. Some of the identified sources in the non-residential survey included computer monitors, the ballast of fluorescent lamps, printers, electric typewriters and equipment isolation transformers.

5. The U.S. National Electrical Code and Magnetic Fields

Ralph Morrison, president of Instrum of Monrovia, California gave an overview of the U.S. National Electrical Code (NEC), its recommendations on grounding practices and the reasons for these recommendations, as well as its effect on magnetic field management.

The U.S. NEC is written, in consultation with a panel of electrical utility representatives, by the National Fire Protection Association (NFPA). This says a great deal about why the NEC exists. Good electrical practice reduces the risk of electrical fires; in addition, the NEC limits the risk of shock exposure to users and electricians. This points out the fact that while disconnecting from the water system may lower ground currents and thus magnetic fields, this has to be weighed against the certain risk from electrical shocks or fires.

The main reason for grounding the neutral at the residence service entrance is for lightning protection. Lightning arriving at the residence should go to earth at this point instead of having to enter the residence to find earth. Once the decision is made to ground the neutral, it follows that the plumbing or other conductors in the building structure must also be grounded to the neutral, otherwise an electrical hazard exists.

A metallic water distribution system is an excellent ground, even compared to ground rod systems. For this reason, even with the current practice of using plastic pipes in the water system, the NEC recommends ground connections to the water service as long as there is at least a 3.05 m (10 ft) conducting service available.

6. Residential Ground Currents: Diagnostics and Possible Fixes

Dr. Stewart Maurer, Professor of Electrical Engineering at the New York Institute of Technology, reported on a study being undertaken for the Empire State Electric Energy Corporation (ESEERCO) in the area of ground currents, magnetic fields, and related electrical and plumbing codes.

In his study, Dr. Maurer found that ground currents fit into one of four categories:

- *Case 1.* The ground currents are due mainly to loads originating within the residence.
- *Case 2.* The ground currents are due mainly to loads originating externally to the residence.
- *Case 3.* The ground currents come from sources both internal and external to the residence.
- *Case 4.* There are no significant ground currents.

A variety of factors can cause any one of these conditions. These factors may occur singly or in combination and can be generalized by the following two conditions:

- An open or deteriorated secondary neutral connection in one or more of the consumer's or utility's neutral circuits.
- Low impedance plumbing paths which present alternate circuits for return currents to flow.

It was pointed out that although ground currents may also flow through such services as cable television shields, these paths have a large resistance (ohms) compared to conductive water pipe (tens of milliohms), leading to insignificant ground currents through the former paths.

A number of methods are available to reduce ground current magnetic fields. Among the two major ones presented were

- Isolation of the primary and secondary neutrals; and
- The use of dielectric unions to break conductive plumbing paths.

Extreme care must be used in these and other methods, because in many cases the "fixes" to reduce ground currents violate electrical safety codes, leading to dangerous situations: a high risk from electrical shocks and fires.

7. Perspectives of Other Utilities

7a. The Water Industry

Robert E. Behnke, of the St. Louis County Water Company, voiced the water utilities' ongoing concerns with grounding of the electrical distribution system to the water system. These concerns are based on two aspects: the safety of their engineers, and current-induced corrosion in conductive pipes.

Water distribution people regularly connect and disconnect meters from the water line. If there is a large potential difference between the two points, electrical shocks can occur. The installation or replacement of water meters is thus an extreme hazard, particularly if the primary neutral connection has been damaged.

Metallic pipe can lose a significant amount of metal per year from just 1 A of *dc* current flowing in the pipe, depending on the type of metal used - 9 kg (20 lbs) for iron, 34 kg (75 lbs) for lead, for example. While the effect of *ac* current is lower, it also has a detrimental effect on metallic pipes. However, many household appliances convert *ac* power to *dc*; for example, diode rectifying circuits are used in hair dryers in converting from full- to half-power modes. If these *dc* currents then flow through the water system, the resulting corrosion can be quite extensive.

One of the methods now being used by water utilities to minimize these problems is to install plastic dielectric couplings in all new service lines so there is no conductive continuity to the water main in the street. This, however, could have some impact on the corrosion of the privately-owned copper service lines in the yards of property owners. Furthermore, this "fix" does not affect old service lines; the expense of retrofitting is quite high.

The water utilities are actively soliciting the NFPA to change the NEC to prohibit the grounding of electrical service to water lines, and instead recommend the use of direct ground rods driven at each residence. Under this proposal all piping interior to the house would be grounded to the rod, but all exterior piping would not be a part of this network, using isolation and dielectric couplings to disconnect.

7b. The Gas Industry

Robert Coe, of the Gas Division of the Public Service Commission of Colorado, gave the perspective of the gas distribution industry on grounding practices. Grounding currents have also been found on gas distribution lines, and may occur there through inadvertent connection of an appliance by a homeowner, or through a connection with the electrical or water distribution system.

Since gas distribution lines are predominantly metallic, the same corrosion problems occur here as in water lines. However, there are additional problems in this case: one major problem is that gas is inflammable. A leak due to corrosion in a gas line can lead to explosive fires. Because of this potential problem, gas companies are very sensitive to leaks, and have traditionally relied on cathodic protection, in which galvanic anodes are used to deter corrosion. Instead of the metal pipe corroding, these sacrificial anodes themselves corrode; they are replaced when the corrosion reaches a maximum level.

A fix that the gas industry has been using is to replace existing lines with plastic pipes. Unfortunately, this is not quite satisfactory because the plastics used are also flammable, and in these situations can release toxic fumes. A leak would therefore be doubly dangerous with this arrangement. In summary, the gas industry recommends more research on grounding problems.

7c. The Telecommunications Industry

Joseph Galow, of U.S. West Communications, represented the telecommunications industry. Their utilities have measured currents as high as tens of amps on the cable shields of their telephone lines. The main concern, from their point of view, is that of noise. Power frequency harmonics, as well as harmonics from equipment such as capacitor banks and household appliances, occur within the voice band (540 Hz) and so can interfere with transmission and reception. While a ground return current of 1.5 A is not a problem, a ground current of 3 A is already noticeable; above 5 A, the noise level can be quite intolerable.

While supporting the reduction of these ground currents, Mr. Galow was of the opinion that it is not a good idea to introduce extra hardware - such as dielectric unions or low-voltage spark gaps - into the system, since this decreases overall reliability.

8. Recent Epidemiological Studies

Dr. Nancy Wertheimer, along with Dr. Ed Leeper, was the first to suggest a possible association of 60-Hz magnetic fields with the development of leukemia in children, through the use of wiring configuration code surrogates for actual magnetic field measurements. At the EPRI workshop, she reiterated her original findings, and presented a re-analysis of a previous epidemiological work by Dr. David Savitz. In that work, Dr. Savitz analyzed 356 cases and controls, and found

a significant increase in risk (OR = 2.8) for children in the highest WL code classification, replicating Wertheimer and Leeper's earlier result (OR = 3.0). However, for actual spot measurements of the magnetic field, there was only a modest increase (OR = 1.6). Incidentally, these results are consistent with the later USC study, described in section 2 above.

Dr. Wertheimer examined the residences in Dr. Savitz' work, in an attempt to find out whether there was a relationship between the magnetic field exposure level, or WL code classification, and the condition of the following:

- Plumbing - conductive or nonconductive;
- Secondaries - open bus or spun triplex; and
- Appliances - off or on.

Based on these classifications, the following conclusions were made:

- For high-current classification homes, the condition of the plumbing did not make any difference in measured fields.
- For other types of homes, those with non-conductive plumbing seemed to have uniformly lower magnetic fields. The greatest reduction appeared in houses with open secondaries.
- For high-current classification homes, the condition of the appliances (off or on) made little difference in measured fields.
- For other types of homes, the average magnetic field rose significantly when appliances were turned on. However, those residences with non-conductive plumbing had lower-than-average fields when appliances were on.

In general, Dr. Wertheimer recommended the use of non-conductive plumbing or spun wire secondaries to lower magnetic fields in houses. Dr. Wertheimer accepted that the Savitz and Peters studies seemed to validate the fact the spot-measurements or 24-hour measurements of the magnetic field had only a weak association with leukemia. However, she also stated that replication of the WL code results showed that there must be some association with magnetic fields. She stated that research has to focus on aspects of the magnetic field other than its strength - for example, harmonics, transients, or the idea that the magnetic field promotes (rather than initiates) cancers.

9. Possible Alternate Grounding Designs

Dr. Ed Leeper, of Monitor Industries, Boulder, Colorado, gave an overview of recent changes in the Colorado electrical system that affect how much load current returns through the neutral wire and how much through the plumbing. Among other things, these changes included the following:

- Replacing open copper secondaries on cross arms by spun aluminum secondaries;
- Using closer spacing to reduce the inductive reactance for current flowing back to the pole transformer by way of the main neutral wire return path; and
- Wire resistances were reduced by going from a typical No. 6 open copper secondary to a typical 2/0 ACSR.

Several changes in plumbing practices have also taken place in Colorado, most notably the increased use of plastic plumbing in water distribution systems. Dr. Leeper made the following observations, which were in accordance with those of Dr. Wertheimer:

- Houses with non-conductive plumbing have, on average, lower magnetic fields.
- The use of spun aluminum wires indicates lower average magnetic fields.

Since the changes in plumbing and electrical wiring practices took place relatively simultaneously, Dr. Leeper pointed out that it was difficult in a statistical study to see which was more important in reducing magnetic fields. However, because of observations by other researchers, the general recommendation was that the best and easiest way to reduce fields in the largest number of houses (neglecting the question of expense) is to eliminate metallic plumbing ground paths from house to house. To accomplish this, Dr. Leeper suggested inserting a dielectric union into the water service line at least 3.05 m from the house, fulfilling NEC stipulations, to isolate the house from the main water line. A further suggestion was to place a ground clamp beyond the dielectric union, and bring an insulated copper wire back into the basement, which would be connected through a low-voltage spark gap to the ground. This device would insure that current would flow if the potential difference exceeds some fixed value. It was mentioned that Monitor Industries manufactures a mechanical low-voltage spark-gap.

10. Focus Groups

After these formal presentations, Focus Groups were organized for in-depth discussions on five general interest areas. Among the topics discussed in the Focus Groups were the following:

- Considerations involving metal pipes (water, gas and sewer) as conductors of ground current.
- Grounding of telephone and cable television facilities.
- Possible revisions to the NEC, and the mechanics of NEC revision.
- Coordination requirements of possible changes that involve many industries and organizations. Mechanisms that need to be instituted to facilitate communications and implementation of changes.
- Brainstorming - concepts for reducing ground current flow on paths other than the electric neutral conductor.

After the Focus Group discussions, the entire group reconvened for a general session. A representative from each Focus Group then summarized the group's discussion.

11. Recommendations

On the basis of the presentations at the Workshop, and personal discussions with other participants, we can make the following conclusions and recommendations:

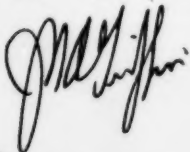
- At present the health risks of magnetic fields are unproven. It is therefore premature to implement mitigation of these fields by decreasing ground currents or by any other means. No active implementation of ground current reduction should be taken unless elevated fields are conclusively shown to pose a danger to the public, or unless legislation forces electrical utilities to arbitrarily limit field levels.
- There exist many technological options to limit ground currents, and thus residential magnetic fields - among them dielectric unions and low-voltage spark gaps. However, these techniques should be considered carefully, as they often lead to dangerous electrical situations. We should note that the expense of implementing these solutions in new electrical/water systems, and in retrofitting older systems, is prohibitively high.

- More research should be done on other possible techniques for mitigating fields. These should focus not only on ground current fields, but also on magnetic fields generated by other sources. Present general research on the possible health effects of magnetic fields should also be expanded. One of the interesting avenues of research that might be pursued is the connection between wiring configuration codes and corrosion in water distribution systems.
- There is a basis for the concern of other utilities when neutral return current flows through their systems. However, the interests of public safety from electrical shock and fires at present outweigh any advantages that may be gained from choosing an alternative grounding system.
- If current grounding practices are to be altered, all utilities that may be affected should be consulted. A consortium consisting of utilities may constitute an appropriate body to consider alternatives to the current grounding practice. However, in any such undertaking, public safety should always be the most important consideration.

12. Summary

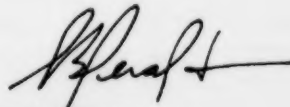
The EPRI Workshop on "Magnetic Field Considerations for Low-Voltage Grounding" provided for many contacts and discussions on the mitigation of ground current magnetic fields. Attendance at the EPRI Workshop yielded other additional benefits as well: for example, personal discussions with contacts at the Workshop led to an extension of collaborative work between EPRI and Ontario Hydro on magnetic field measurements at the Magnetic Field Research Facility in Lenox, Massachusetts. Overall, the experience gained at the Workshop should prove important in characterizing electromagnetic field mitigation techniques in the Canadian context.

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